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DISCUSSION OF REGIME THEORY FOR SELF-FORMED SEDIMENT-BEARING CHANNELS

(Published in May, 1951)

By Emmett M. Laursen, Gerard H. Matthes, and T. Blench

IRRIGATION DIVISION

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DISCUSSION

EMMETT M. LAURSEN,[23] ASSOC. M. ASCE.—The author will probably frankly admit that his three equations of regime (Eqs. 3, 4, and 7) are empirical, and that any attempts to rationalize them are simply efforts to integrate specific observations into a more general body of empirical law, thereby increasing the confidence with which they may be used. This comment must not be taken as a criticism since fundamentally all scientific knowledge is empirical—that is, based on observed facts; and "laws" are true if, and only if, they allow the prediction of future conditions. Whether the regime equations achieve general acceptance will depend on further measurements extending the limits of observation, rather than any rationalization. The following analysis may aid in the interpretation of the author's regime theory: first, by outlining the relations necessary for the solution of the problem, and, second, by examining the factors involved in the constants of his equations.

Only the Manning equation $\left(Q = \frac{1.49\, R^{\frac{2}{3}}}{n} A \sqrt{R\, S} \right)$ and two assigned values are needed for the solution of flow in a rigid channel. For any cross-sectional shape, the value of the hydraulic radius, R, is determined by the area, A. The material of the channel, of course, determines the value of the roughness coefficient, n. If the quantity, Q, is known, the one equation gives a relation between the two unknowns (the area, A, and the slope, S) such that the choice of one fixes the other. Usually, this choice is based on economic balancing of costs.

The freedom of choice disappears, however, when a certain load of sediment must be transported in a lined channel. Since existing transport equation are generally similar in form, the argument does not depend on which is selected. The Schoklitsch equation[24] is used merely for illustration:

$$G = \alpha\, (Q - Q_O)\, \frac{S^{\frac{3}{2}}}{\sqrt{D}} \qquad (23)$$

in which D is the diameter of the sand in mm; α is a variable coefficient; and Q_O is a critical term. Despite the introduction of a second equation, the solution of this problem is still straightforward.

If, now, a channel that is self-formed in alluvium is considered, the shape is no longer a matter of choice but is determined by the flow and sediment characteristics. A third equation is necessary to replace the former arbitrary choice of shape, and the author's second equation of regime represents an example of this desired relationship.

Although the three equations of regime, as advanced, are mathematically sufficient for the complete solution of the problem, their usefulness is open to a

NOTE.—This paper by Thomas Blench was published in May, 1951, as *Proceedings-Separate No. 70*. The numbering of footnotes and equations in this Separate is a continuation of the consecutive numbering used in the original paper.

[23] Research Engr., Iowa Inst. of Hydr. Research, Univ. of Iowa, Iowa City, Iowa.

[24] "Engineering Hydraulics," ed. by Hunter Rouse, John Wiley & Sons, Inc., New York, N. Y., 1950, p. 795.

specific criticism. Just as the successful use of the Manning equation depends on the judgment employed in selecting the correct value of n, the successful use of the regime equations depends on the selection of the constants B, s, and C, not to mention the question that still remains as to the validity of the relationships for other than conditions in India. Unfortunately, very few engineers have the requisite experience to exercise such judgment.

To assess the physical significance of the author's regime theory, the foregoing analysis may be carried to a parallel form. A guide to the selection of coefficients will be provided in that way. Eq. 23 may be combined with the Manning equation and rearranged to give

$$\frac{V^2}{d} = \frac{2.2\, d^{\frac{1}{6}}}{n^2}\left(\frac{G}{Q - Q_o}\frac{\sqrt{D}}{\alpha}\right)^{\frac{2}{3}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (24)$$

so that the bed factor (B) becomes

$$B = \frac{2.2\, d^{\frac{1}{6}}}{n^2}\left(\frac{G}{Q - Q_o}\frac{\sqrt{D}}{\alpha}\right)^{\frac{2}{3}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (25)$$

It may be expected, therefore, that the value of B will vary beyond the limits of 0.6 to 1.25 (as given under the heading "Generalized Regime Theory: Practical Regime Formulas"), if conditions are markedly different from that of the Indian plains. That is, the factors implicitly involved in the bed factor are now explicit. Unfortunately, every bed-load formula will give a relation that is slightly different, although composed of essentially the same parameters.

By rearranging terms, the third equation of regime can be put in a form parallel to the Manning equation:

$$V = (C\, g)^{\frac{1}{2}}\left(\frac{V\, b}{\nu}\right)^{\frac{1}{6}}\sqrt{dS} \quad \ldots\ldots\ldots\ldots\ldots\ldots (26)$$

This is equivalent to saying that the Manning evaluation of the Chezy coefficient is given by

$$\frac{1.49\, d^{\frac{1}{6}}}{n} = (C\, g)^{\frac{1}{2}}\left(\frac{V\, b}{\nu}\right)^{\frac{1}{6}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (27)$$

The use in this equation of the generally accepted Reynolds number based on depth would seem more appropriate, since in a wide channel the depth rather than the width characterizes the flow. However, it might be pointed out that since the Reynolds number is raised to the $\frac{1}{6}$ power, by including an appropriate constant the evaluation of the Chezy coefficient would differ by only $\pm 12\%$ for the range of b/d from 5/1 to 30/1. Thus, $\dfrac{1.37\left(\dfrac{V\, b}{5\,\nu}\right)^{\frac{1}{6}}}{\dfrac{V\, b}{\nu}} = 1.12$; and, $\dfrac{1.37\left(\dfrac{V\, b}{30\,\nu}\right)^{\frac{1}{6}}}{\left(\dfrac{V\, b}{\nu}\right)^{\frac{1}{6}}} = 0.90$. Any other factors that might affect the value of the

coefficient, such as roughness or sediment transport, must be contained in the author's C term. Hence, in the application of the regime theory to areas other than India, cognizance should be taken of a possible variation in the recommended numerical values, as well as in the function itself.

By combining the first and second equations of regime, a width-depth relation may be obtained:

$$\frac{b}{d} = V\frac{B}{s} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (28)$$

This relation expresses explicitly the factors determining a self-formed shape. As E. W. Lane,[25] M. ASCE, has pointed out, a high width-to-depth ratio is required if the sediment load is large or if the bank material is easily erodible. The variations in the factors B and s, as given by the author, agree with this interpretation. To question the inclusion of the velocity, V, in the relation is actually a question of why V occurs to the cube in the second equation of regime and to the square in the first. The writer's only comment would be that the first equation is a modified transport equation and the second, somehow, a critical equation that is applicable when erosion begins. The corresponding derivation of the author's appendix is incorrect, because $\tau = \mu\frac{V_\delta}{\delta}$.

Therefore, Eq. 22 should read

$$\tau \alpha \frac{\rho\left(\frac{\nu V^3}{b}\right)^{\frac{1}{3}}}{\frac{1}{2}\,1\,n\frac{V\,b}{\nu}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (29)$$

Moreover, the assumption that $\frac{\delta}{b}\alpha\left(\frac{V\,b}{\nu}\right)^{-\frac{1}{3}}$ is questionable for a wide channel.

The author advances three relations of the type necessary for the solution of self-formed, sediment-bearing channels. Whether the simple forms advocated will be modified or supplanted in the future will depend on further measurements, especially of channels outside the Indian plains area for which the original equations were derived. Even assuming that the form of these equations may eventually prove to be valid, a high degree of judgment will still be required for the selection of numerical values of the factors B, s, and C in the equations. However, the relations do offer at the very least a method of solution that does not depend on pure guess or assumption.

GERARD H. MATTHES,[26] HON. M. ASCE.—The engineering profession is indebted to the author for having sketched the growth of the regime theory and for having illustrated its application to practical problems. Although the author tactfully has refrained from expressing wonderment at the scant interest shown in this theory by American engineers, it is clear that his able paper is designed to awaken their interest in the subject. Undeniably, formulas that over a period of more than a quarter of a century have proved of consider-

[25] "Stable Channels in Erodible Material," by E. W. Lane, *Transactions*, ASCE, Vol. 102, 1937, p. 123.

[26] Cons. Hydr. Engr., New York, N. Y.

able worth in the hands of the irrigation engineers in India are entitled to better recognition in the United States. The fact that interest in them has lagged in this country is due to certain conditions that also need recognition. The object of this discussion is to make this aspect clear.

Considering first R. G. Kennedy's well-known formula $V_k = 0.84d^{0.64}{}_k$, it is unfortunate that from the start in the United States it was called a formula for "nonsilting, nonscouring" channels. Unfortunate, also, was the fact that for a long time American engineers were not aware that the term "silt" as used by British engineers in India included all materials from the finest grain sizes to gravel, stones, and boulders. Thus, in the case of the large flows diverted from the rivers in the Punjab into irrigation canals capable of carrying 10,000 (or more) cu ft per sec, with which Mr. Kennedy was concerned, the "silt" entrained included gravel in sizes up to 1-in. and $1\frac{1}{2}$-in. sizes. Although most of this coarse bed-load material was prevented from entering the canals at the headworks, a certain volume of it did enter the canals. The writer's analyses of the original Kennedy data have indicated to him that the formula is distinctly an empirical tractive force formula, aimed at preventing these coarser materials from forming deposits in the canals. The finer materials in suspension (that is, that portion which American engineers designate as silt) were thus automatically prevented from forming deposits, but the formula primarily was not aimed at these finer materials. In other regions where the bed-load material is of a different type, the Kennedy formula has required different coefficients as well as exponents.

On August 24, 1939, the writer had a conference with Sir Claude C. Inglis (M. ASCE), then Director of Central Irrigation, India, and C. M. White of Imperial College, London, when these gentlemen visited the lower Mississippi River. During the conference the writer inquired whether the Kennedy formula was still felt to be satisfactory. He was assured that it was. Inquiring further, about trouble with sedimentation when canals are operated at part capacity, he was told that since the canals in India were operated only at the full capacity for which they were designed, or "not at all," sedimentation had been small. The writer explained, in turn, that this plan of operation, however desirable, could not be followed in the arid regions of the United States where scarcity of water did not tolerate running canals full and wasting the unused surplus. Consequently, he explained, irrigation canals frequently must operate at part capacity, inviting settlement of all grades of sediment and requiring periodic cleaning out; for these reasons American irrigation canals can not be designed on the basis of a Kennedy-type relation.

The foregoing is cited as it has an important bearing on the underlying philosophy of the regime theory evolved by Gerald Lacey. That theory fundamentally has the same basic concept that actuated Mr. Kennedy; namely, it applies only to bank-full flow, whether in canals or in natural channels. The canals have shown that they are self maintaining when operated as described. Rivers at bank-full flow are known to recondition their channels, provided they flow in "noncohesive" alluvium, which may consist of silt, sand, or gravel (shingle). When rivers are reconditioning their channels, they are said to be "in regime," according to Mr. Lacey. However, bank-

full, dominant, or regime flow (all synonymous terms) is only one of the many stream-flow conditions that engineers are confronted with in their day-by-day river problems. In most of their problems the regime formulas do not apply or are of no assistance. Furthermore, many alluvial rivers in the United States have become affected by contraction works, bank revetment, channel shortening, and encroachments on their widths; according to Mr. Lacey, his regime formulas are not applicable in any of these cases. This situation places many limitations on the use of regime formulas in the United States. Conceivably, the author may still find a field for their application in Canada, where alluvial rivers have suffered relatively little as yet from restraints imposed by man.

T. BLENCH,[27] M. ASCE.—The fundamental points raised by Mr. Laursen are treated in detail by the writer in other publications.[28, 29] The following reply to Mr. Larsen is based on that treatment.

Human needs required that rigid-boundary hydraulics be a practical subject long before knowledge of fluid motion within rigid boundaries reached even its present inadequate form. So theoretical development was marred by "plausible assumptions" (often obscured by mathematics slightly beyond ordinary engineering standards), by a neglect of essential variables, and by a failure to test theories over a wide range of variables. The compilation of tables and charts containing "variable constants" has served to make these results serviceable in practice. As a result the science has advanced under the stigma of "empiricism." Gerald Lacey, who founded modern regime theory as applied to mobile boundaries, followed the normal routine of scientific investigation by correlating measurable variables. He used these variables to define measures of intangible variables over the entire range encountered in practice; and he sought to express correlations as simple functional relationships containing dimensional or nondimensional groups of magnitudes with definite physical meanings. The foundation laid by Mr. Lacey has served his successors so well that regime theory is now empirical only in the sense that all physics is empirical.

It is true that rigid-boundary and flume transport formulas can be used (instead of the better regime formulas) to demonstrate that the three degrees of freedom in most regime channels require three independent equations. Nevertheless, the development of a working theory from such formulas is not recommended. For example, the use of the popular Manning formula to fix one self-adjusting variable is tempting; but that formula, in spite of its implicit dimensional soundness, is merely a mathematical alternative to the Kutter formula with its dimensionally incongruous "variable constant" and its unsatisfactory background. When the formula was applied to regime canals, n had to be given values ranging from 0.018 to 0.0225 to explain the behavior of channels of the one system with discharges ranging from several thousands to a

[27] Assoc. Prof., Civ. Eng., Univ. of Alberta, Edmonton, Alta, Canada; and Consulting Engr.

[28] "Hydraulics of Sediment-Bearing Canals and Rivers," by T. Blench, published privately (Evans Industries, printer), Vancouver, B. C., Canada, 1951.

[29] "Civil Engineering Reference Book," Butterworth Scientific Publications, London, England, 1951 (Chapter on Rivers and Channels).

few units of cubic feet per second. (This misbehavior of the formula, with n a function of discharge, cannot be detected in ordinary rigid pipe work, where size range is small and is accompanied by genuine changes of roughness.) However, in the absence of a correct formula, the Manning formula can be used as in the past.

The second degree of freedom in regime channels can be disposed of by solving Eq. 23 with Eq. 24, but the result (Eq. 25) makes the bed factor B depend on four quantities:

(1) n, which the computer must guess, really depends on the other terms. (It is a function of Q because of the empirical derivation of the formula that defines it);

(2) G, which cannot be measured, in practice;

(3) Q_o, which is a vague "critical term"; and

(4) α, which is a "variable coefficient" that cannot be assessed with assurance, and whose nature needs to be further explained.

Regime theory teaches that channels carrying the same water-sediment complex have the same values of B. Under such circumstances, the right-hand side of Eq. 25 is constant, which makes the equation appear as an "empirical" formula, in the very worst sense of that word, in which the depth is related to a mass of nondeterminable interrelated parameters which are associated somehow or other with the nature of the complex. This example shows why the use of rigid-boundary equations mixed with flume transport formulas has had little success in the design of regime channels.

With even the best transport equations in use, the extent of the current basic ignorance is obscured (not removed) by the several practically unassessable terms involved. In the case of regime equations, the ignorance is concentrated in the quantity B, and this fact is generally recognized. Actually, however, the practical estimation of values of B by an experienced engineer is not much worse than the selection of n-values by inspecting the material in a rigid boundary.

The constant C is fixed for all conditions, as defined implicity in the sentence following Eq. 12. For practical purposes s need not be evaluated to a fine degree of accuracy; even a novice can determine its value without trouble (see heading "Generalized Regime Theory: Practical Regime Formulas"). Except for the unfortunate separation of flume-transport experimenters from regime knowledge there might now be a reasonable formula linking B with the sediment factors on which it depends. Instead, a great deal of potentially useful experimentation seems to have been wasted in observing nonregime (and, therefore, unspecifiable) conditions. Unrealistic materials were used in testing formulas with little scientific background. There are noteworthy exceptions, and the prospect of correlating B with its several constituents seems bright. The prospect would improve if original data of earlier tests were made available.

The third degree of freedom would be disposed of exactly as in regime theory. An expression is found for tractive force intensity over the sides, the upper and lower limits of which are determined by the nature of the sides and by the water-

sediment complex. However, the relevant theories of rigid-boundary hydraulics are related to concepts involved in the flow formula; and the two theories are still in conflict. The widely advocated logarithmic type of flow formula does not fit practical conduit data[14,30] any better than do the tests of regime channels (see Fig. 1). A revision of laminar film theory is needed so that s can be explained as attempted in Appendix I. In fact laminar films should now be explained quantitatively in terms of data observed on large conduits and regime channels instead of in terms of assumptions that lead to formulas that are inconsistent with those data.

Mr. Matthes states correctly that the object of the paper is to awaken interest; but the writer denies that he is surprised by the backwardness of the subject in the United States. It took a long time to develop interest in India where the facts were readily available for analysis. Little advance can be expected until the subject is presented as a whole in accessible form. The case

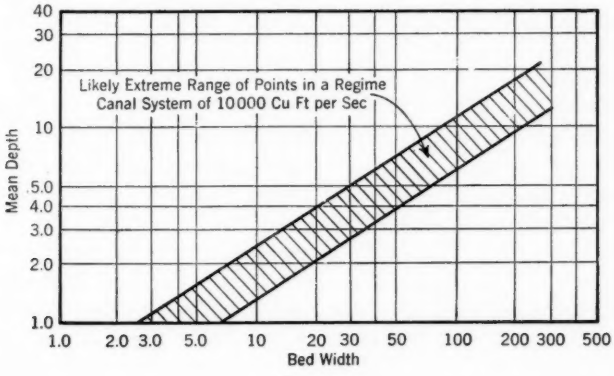

FIG. 4.

is analogous to that of rigid-boundary pipe flow, where the prerequisite to a clear understanding is a plot of observed friction factors against the fullest available range of Reynolds numbers. Such a plot demonstrates that there are three distinct transitions that yield to no obviously simple expression. Unless the whole physical picture is seen and appreciated, investigators must be expected to continue experimenting with their own little assortments of mixed data, deriving contradictory and unintelligible flow formulas and accusing each other of "selecting data." In this paper and elsewhere,[28,29] the writer has tried to make the new knowledge available and to outline its complete picture. Once the reader has understood it, and has acquired a sense of proportion, he will find that engineering ingenuity will permit him to obtain reasonable approximate solutions to most, if not all, of the problems that Mr. Matthes very reasonably believes to be insoluble. The sense of proportion is not easy to obtain by reading. For example, Fig. 4 is derived from a drawing presented[31] by E. W. Lane. It shows two lines between which the writer would expect

[14] *Transactions*, ASCE, Vol, 113, 1948, p. 1067.

[30] "A Revised Manning Flow Formula," by Thomas Blench, *Technical Bulletin No. 2*, The Engineering Institute of Canada, Ottawa, Ont., Canada, June, 1950, p. 7, Figs. 1 and 2.

[31] "Stable Channels in Erodible Material," by E. W. Lane, *Transactions*, ASCE, Vol. 102, 1937, p. 130, Fig. 2.

points, taken from a regime canal system of 10,000 cu ft per sec, to lie with a scatter that depends largely on the way in which real canal heads distribute sediment load among the individual channels. Obviously, the mass of data required to prove or disprove regime theory will be very great until enough has been learned to justify scientific selection; yet the inexperienced would probably test their theories in terms of half a dozen points or by taking points from different systems. For actual application, the writer has yet to find a report of the misbehavior of American rivers, which shows a state of affairs that was unforeseeable or even unassessable. When he visited the All-American Canal (Arizona-California), he found that he could predict the order of slope and width-to-depth ratio for well-behaved large channels from the corresponding data for small channels; and he could even estimate the order of size of the bed material. Perhaps most noteworthy is the fact that an analysis of model scales of the United States Waterways Experiment Station at Vicksburg, Miss., since 1938, shows them to follow regime theory very closely although they were determined, apparently, by prolonged trial and error.[32]

Sir Claude Inglis' quoted views of 1939 on the Kennedy formula seems to have been revised[7] by 1949. Possibly he did not feel inclined to condemn, completely, in a place where no alternative was known, a formula that had some empirical value. Furthermore, the reasons for running canals full or closed seems to have been misunderstood. Distributing channels are run full because equitable supply under conditions of limited command would be impossible any other way; but the branches from which these distributing channels are supplied are run partly full and are "headed up" at control points. Incidentally the "heading up" results in temporary inactivity of the bed, and regime analysis would be applied only to full supply conditions when the bed is active.

Even if data for rivers in India were collected to the limit of their availability on the North American continent, there seems to be no prospect that there would be any improvement in the nature of those data or in the extension of their range. The discharge range covers the largest canals ever built; the sediment loads include examples comparable with those of the Colorado River; the bed materials include all sizes in the sand range; the Reynolds numbers (in terms of breadth) are many times greater than the maximum laboratory values and compare with those of the world's largest conduits; slopes are measured with great accuracy (the laboratory cannot measure them as accurately); and widths are self adjusting, negatively as well as positively. The most potentially fruitful line of advance in North America seems to be in applying the theory to existing canals and rivers. Its application, like that of rigid-boundary hydraulics, requires some training, experience, and familiarity with phenomena observed in the field. Unfortunately, only two colleges in North America teach the subject.

The writer acknowledges that Eq. 22 should have a sign of proportionality instead of a sign of equality. The implications of the formula then depend on the definition of laminar film thickness, leading to a lengthy discussion beyond the scope of the paper.

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[32] "Scales for Moving-Bed Models," by T. Blench, Dock and Harbour Authority, London, England, March, 1951, p. 353, Fig. 1.

[7] "The Behaviour and Control of Rivers and Canals," by Sir Claude C. Inglis, *Publication No. 13*, Govt. of India Central Waterpower, Irrigation and Navigation Research, Yeravda Jail Press, Poona, India, 1949.

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112	Feb., 1952	"Diversions from Alluvial Streams," by C. P. Linder	July 1
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117	Mar., 1952	"The Development of Stresses in Shasta Dam," by J. M. Raphael	Aug. 1
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